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Design, fabrication and characterization of a capacitatively coupled RF discharge plasma system

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Abstract A capacitatively coupled radio-frequency discharged plasma in the discharge tube of cylindrical topology with low-cost components is fabricated Argon plasma is produced at 10^{-3} mBar pressure and electron density is estimated We also estimate conductivity of plasma Thereafter, we propose an analytical model of our experimental set-up and compare the results

Keywords Capacitatively coupled rf discharged plasma, design and fabrication electron density, conductivity of plasma

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1. Introduction

The importance of the electrodeless plasma discharges is well familiar if the gas in the system requires to be maintained in high purity condition [1-3]. Breakdown of gas can be made through electrodeless process by high frequency (hf) breakdown [4]. High frequency electrodeless breakdown can be done in either of two processes namely, (a) induction discharges (I-discharges) and (b) polarization discharges (P-discharges). A free electron in a vacuum under the action of an alternating field oscillates with a velocity 90° out of phase with the field in a steady state and hence takes no power on the average from the applied field. The electron can gain energy only by suffering collisions with the remaining neutral gas atoms [5]. The essential criterion for the high frequency breakdown is that the mean free path of the electron should be small compared to the linear dimension of the plasma discharge tube and the frequency of oscillation should be less than the electron gas collision frequency [6].

We study the case of polarization discharges in which the experimental gas is kept at very low pressure in a discharge tube of cylindrical topology kept between two semi-cylindrical electrodes forming the capacitative coupling.

In the present paper, we first describe a low cost indigenous experimental set-up for a capacitatively coupled rf discharged plasma made up of argon gas at very low pressure and a few experimental plasma parameters like electron density from which we estimate the conductivity. Next, we propose an analytical model and the estimated parameters from our model are finally compared with the experimental results. The cost of the three-phase power supply is about Rs. 30,000 and the cost of the RF oscillator is about Rs. 1,00,000 including diagnostics probes. The fabrication cost of the whole set-up is about one-third of the system available from the market.

2. The experimental set-up

The basic plasma system is composed of three parts-namely, (a) the power supply unit, (b) the plasma generator and (c) the discharge tube where gas is ionized and taken to the plasma state. These three units may be clearly seen in the Figure 1 depicted by block diagrams for simplicity. The power supply must be able to sifficiently pump energy to the plasma.

For our case, we designed and fabricated a three phase 1A (limiting, which can be changed) 6 KV DC power supply as shown in the Figure 2. To enable easy and safe control

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mechanism, we incorporated one single phase 220V/5A contactor to switching the power supply. The transformer for the power supply was fabricated by the Variable Energy Cyclotron Center (VECC), Kolkata in the *delta–star* topology.

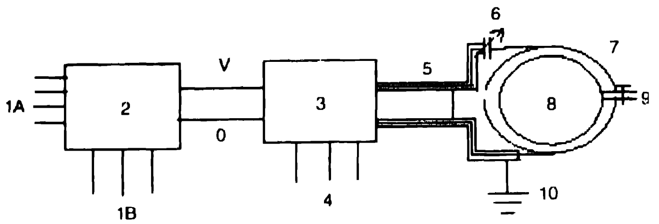


Figure 1. The block diagram of the experimental setup 1A 3 phase power line, 1B 220 VAC, 50 Hz, 2 3-phase DC power supply, 3 Radio frequency oscillator, 4 220VAC, 50 Hz for heating the filament, 5 coaxial cable with the outer braid earthed, 6 Gang used for fine tuning the plasma resonance, 7 copper plate behaving as antennae, 8 borosil glass made cylindrical discharge tube, 9 gas in/outlet, 10 Earthing of the braid, V and 0 denote the DC voltages

POWER SUPPLY FOR RF DISCHARGE PLASMA

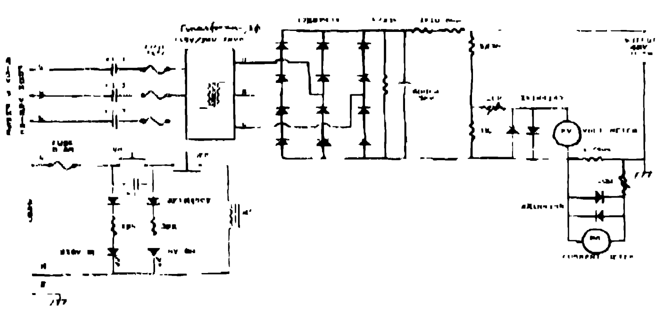


Figure 2. Schematic circuit diagram of the three phase power supply

Next important block is the plasma generator. Usually, plasma generator is an oscillator which can produce signals at high frequencies. We have also designed and fabricated one such oscillator. The active elements comprises of two BEL-300 triode valve. Valve tubes are used because they can be used for few hours continuously with high current rating. Porcelain grid caps are used for better connectivity to the valves. The valve tubes are operated with push-pull oscillator architecture for producing a continuous oscillations. The resistance R_g and capacitance C_g facilitates the push-pull operation with feed back. The filament is connected with some 9V/1A transformers for heating, and bypass capacitances are used for bypassing the oscillatory current to the ground. The oscillation is resonated by using one tank circuit comprised of inductor L_T and capacitor C_T as depicted in the Figure 3. High voltage DC is supplied through one RF choke to the tank inductor by tapping at the middle. A precautionary measure has been taken here which restricts oscillation from L_T to enter the power supply using one high capacitative capacitor connected to the ground so that only DC connection is made between the power supply and the tank circuit.

The discharge tube considered in our experiment is of cylindrical topology made up of Borosil glass having two gas flow nozzles fitted with the vacuum-tight stop cock. The dimension parameters of the discharge tube are l_d = length = 25.0 cms and r = radius = 6 cms.

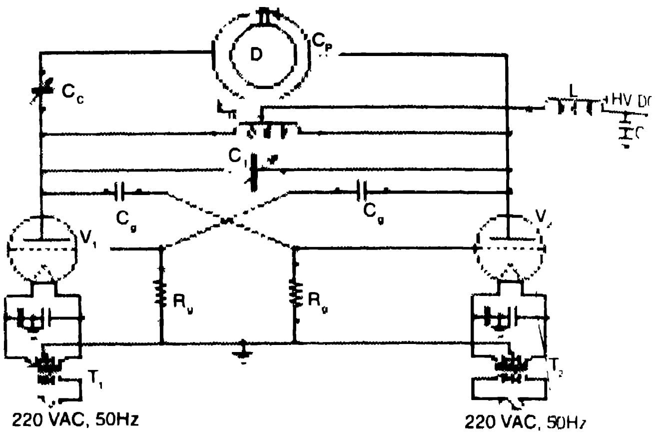


Figure 3. C_c tuning capacitor, C_g grid capacitor, C_p plasma capacitor formed by electrodes, C_t tank capacitor, D borosil glass discharge tube, L choke (RF), L_t tank inductor, T_β transformer for filament heating (β = 1, 2), V_γ · BEL-300 vacuum triode values (γ = 1, 2)

Figure 3 also depicts that two copper plates blanket the discharge tube in the same cylindrical topology as the tube itself. These copper plates called as *antennae* are connected to the RF oscillator *via* two coaxial coils. Now coaxial coils basically connect the antennae to the tank circuit. The tank circuit has floating RF potential and hence the antennae must have floating potential. To diminish the effect of the screening and decreasing the energy loss, the outer braid of the coaxial cable is earthed. Now, it may happen that placement of the antennae has some minor shift such that the axis of the discharge tube does not coincide with the axis of the antennae. In that case the field imposed upon the gas inside the tube will have some shear due to non-uniform field. Also the plate of the antennae may have some minor bends so that field imposed in the gas will have some shearing effects. To correct this error one may place the antennae properly with micrometer screw-gauge adjustment so that the field becomes uniform. Otherwise, one may simply put some multi-turn high voltage metallic gang C_t for fine tuning the RF field in series as shown in the Figure 3. This matching capacitor is useful at least in the first place of approximation.

To protect the environment from the RF leaking, one must put the active elements of the tank circuit within some metallic braid cage and the cage should be earthed so that no emission can come out of the cage. It is also better to put the discharge tube in another metallic wire-mesh cage so that no emission can come out of the cage as per the international norms of the radiation safety [7, 8].

3. The analytical model

Since the two semi-circular cylindrical copper plates kept at potentials V and 0 behaving as antennae, cover the discharge tube in cylindrical topology, we use the cylindrical coordinates system such that the z-axis is considered along the length of the tube and the origin is kept at the center of any of the two ends. We also assume that the field component along the length is uniform and the bending of fields at the ends is neglected for the simplicity. Therefore, any field $\psi(r, \phi, z)$ defined in our system of cylindrical topology within the discharge tube can be represented as

$$\nabla^2\psi = 0, \tag{1}$$

or

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\psi}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2\psi}{\partial\phi^2}=0, \tag{2}$$

so that Laplace's equation is satisfied. Here, we have assumed that the variation of the field along the length is negligible *i.e.* we used the assumption $\partial\psi/\partial z = 0$ and the plasma is quasi-neutral. Solving the eq. (1) for (r, ϕ) plane, we get

$$\psi(r, \phi) = \frac{V}{2}+\frac{2V}{\pi}\sum_{n=0}^{\infty}\left(\frac{r}{a}\right)^{2n-1}\frac{(-1)^n}{2n-1}\cos(2n-1)\phi. \tag{3}$$

Solving for the (r, ϕ) plane, the electric field E applied on the plasma discharge system by the external source is given by

$$E^2 = \frac{V^2}{\pi^2}\cdot\frac{4a^2}{\left(a^2+r^2\right)^2\cos^2\theta+\left(a^2-r^2\right)^2\sin^2\theta} \tag{4}$$

which for semi-circular configuration leads to expression of energy stored in the capacitor as

$$\int E^2 d\tau = \frac{4V^2 l_d}{\pi}\ln\frac{a-\delta}{\delta}. \tag{5}$$

where, $d\tau$ is the elementary volume element.

Here, δ is the separation between the two semi-circular plates, l_d is the length of the discharge tube, a is the radius of the discharge tube. Using this equation and expression of energy for semi-circular capacitors, one may write down the expression for the capacitance of the antennae used on the discharge tube as

$$C = \frac{8l_d}{\pi}\ln\frac{a-\delta}{\delta}. \tag{6}$$

Next, we consider two cases, namely, the plasma discharge is off and the plasma discharge is on. To analyze the circuit, let us consider that oscillator frequency is f when the plasma is discharged, such that $\omega = 2\pi f$. Let the RF field be e, L_T is the inductance in the tank circuit having inductor resistance R_L and C_T is the capacitance of the tank circuit. Let C is the tuning capacitance, C_P is the plasma capacitor. Then, we may write the expression for an equivalent capacitor C_1 such that $C_1 = (CC_P + C_PC_T + C_TC) / (C + C_P)$. Now, if the plasma discharge is switched on, then the plasma discharge resistance R_d is given by

$$R_d = \frac{\rho\delta}{A} = \frac{\delta}{\sigma A} \tag{7}$$

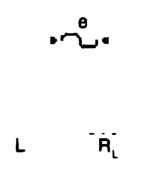
where δ = distance between the two copper plates, A = area of cross section of the discharge tube having radius $r = \pi r^2$ and length l_d, σ = conductivity in the plasma environment.

For the sake of simplicity, one may neglect R_l – the inductance impedance and this consideration does not loose any physics in the analysis as $R_L \sim 0.04$ Ohm, *i.e.* very small. This helps us to write down the expression for the admittance of the circuit while the plasma discharge is on as followed :

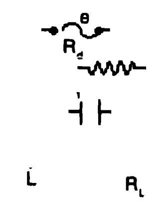
$$Y| = \frac{\omega_3^4 L_T^4 + \omega_3^2 R_d^2\left\{C_1\omega_3^2 L_T^2 - L_T\right\}^2]}{R_d\omega_3^2 L_T^2} \tag{8}$$

Now, the admittance needs to be minimized in order to increase the impedance of the circuit which is essential to ignite the plasma which otherwise pumps out the net power to ground. The plasma capacitor will otherwise behave as a simple good conductor only which is not desirable. The admittance is minimized for numerator equating to zero resulting in the determination of the expression for ω_3 as :

$$\omega_3^2 = \frac{\left(2C_1R_d^2L_T - L_T^2\right)\pm\sqrt{\left(L_T^2-2C_1R_d^2L_T\right)^2-4\left(R_d^2C_1^2L_T^2\right)R_d^2}}{2\left(R_d^2C_1^2L_T^2\right)} \tag{9}$$



Plasma capacitor is present without discharge



Plasma discharge is on through plasma capacitor

Figure 4. The figures show equivalent circuit diagram for experiment before plasma discharge and during plasma discharge.

Putting the value of R_d, one may determine the expression for the plasma conductivity as :

$$\sigma^2 = \frac{\delta^2}{L_T^2 \omega_3^2 A^2}\left(C_1 L_T \omega_3^2 - 1\right)^2$$

or, $$\sigma = i\frac{\delta\left(C_1 L_T \omega_3^2 - 1\right)}{L_T \omega_3 A} \quad (10)$$

The *imaginary* value of σ obtained from eq. (10) indicates that plasma can sustain in this experimental condition at the cost of power given to the system. From the numerical value of this $|\sigma|$, one can estimate electron density.

Using the Chapman-Appleton model of plasma, the plasma conductivity can be given as

$$\sigma = \frac{n_e e^2 \nu_e}{m_e\left(\nu_e^2 + \omega_3^2\right)} \quad (11)$$

where ν_e is the electron collisional frequency. The maximum value of conductivity is achieved for $\nu_e \approx \omega_3$ which yields

$$\frac{n_e e^2}{2m_e \omega_3} \quad (12)$$

which can provide the electron density as

$$n_e = \frac{2m_e \omega_3 \sigma_{\max}}{e^2} \quad (13)$$

4. Measurement

In our experimental set-up, the primary data are δ = 0.015 m, l_d = 0.25 m, r = 0.06 m, f = 13.0 MHz, C_l = 37 nF, C_p = 188.6 pF, C = 189.5 pF, R_l = 0.04 Ohm, L_T = 4.1 µH. Hence, the value of C_1 is 37.095 nF. From eq. (10), the magnitude of the conductivity can be given as 4.02 Siemens. Using eq. (13), one can determine the electron density (n_e) as 2.32737×10^{16} m^{-3} [9]. The atomic density of the discharge tube is 2.42×10^{17} m^{-3}. The degree of ionization is determined as the ratio of the electron density and atomic density and is of the order of 0.095.

5. Conclusion

In this paper, a low-cost indigenous experimental set-up for capacitatively coupled RF discharged plasma system using argon gas at very low pressure is presented. We have analysed transient classical phenomenon at the onset of plasma. It is very much vital to have some estimation of the parameters arising from various transient recombination occurring during seeding. These results are consistent with the diagnostics with probes [9]

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